TURBULENCE RELATED TO THE CHARACTERISTICS OF FREE JETS

BY

JOHN FREDERICK TAYLOR

B.S., Louisiana State University, 1945
M.S., University of Illinois, 1948

AN ABSTRACT OF A THESIS

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN CHEMICAL ENGINEERING
IN THE GRADUATE COLLEGE OF THE
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Introduction

There are a number of important engineering applications in which a jet of fluid entrains and mixes with an other fluid. These include the simple mixing of fluid streams, entrainment in jet pumps and ejectors, spray drying, the combustion of gas, oil, and powdered coal, and gas phase chemical reactions. This paper describes experiments with a jet of air issuing into the air of the room at the same temperature as the room. The influence of nozzle design, nozzle discharge velocity, and turbulence conditions at the nozzle discharge on the properties of the free jet are reported.

The flow in a free jet is unique in that the turbulence levels are approximately ten times those normally encountered in flow systems. As a result, the effects of the turbulent velocity fluctuations on the jet properties are important. The instantaneous velocities may be considered as made up of an average velocity and a fluctuating velocity such that the time average of the instantaneous velocity is the mean velocity and the time average of the fluctuating velocity is zero. The square of the fluctuating velocity is finite however, and the average of the square of the instantaneous velocity is not equal to the square of the mean velocity. An impact tube was used in this work to determine the jet properties, and the quantity measured was the square of the instantaneous velocity. This is not directly related to the mean velocity but requires also a knowledge of the mean values of the squares of the fluctuating velocities. Since the entrainment characteristics of the jets are computed from the mean velocities, the impact tube data was corrected for the effect of the fluctuating components of the instantaneous velocities.

Experimental Apparatus

The experimental apparatus consisted of a source of 300 scfm. of compressed and filtered air, a flow control and temperature control system, a flow nozzle, a calibrated impact tube that was used to measure the axial component of the momentum flux, and a mechanism for traversing in three dimensions. The accuracy of calibration of both the metering elements in the flow control system and the impact tube was of the order of 1%. Several nozzles were used, all having an ASME long radius-low ratio type (2) approach section but having different throat diameters, throat lengths, and exterior designs.

Results and Conclusions

Profiles were taken of the x-component of the momentum flux velocities ($\sqrt{\overline{u^2}}$ along the axis of the jet and across planes perpendicular to the jet axis at distances from the nozzle of 0.5, 1.0, 2.0, 3.0, 4.0, 6.0, 8.0, 10.0, 15.0, 20.0, 25.0, and 30.0 nozzle diameters for nozzle discharge velocities from 100 to 800 ft./sec. The radial distributions of the momentum flux velocities were considered for three regions of the jet at successively greater distances from the nozzle: a region that included a potential cone or zone of constant momentum flux velocity equal to the nozzle discharge velocity, a transition region, and a region of developed flow. In the region of the potential cone, an empirical correlation was obtained for the flow field surrounding the potential cone as follows:

$$\frac{\sqrt{\overline{u^2}}}{\overline{u_o}} = f\left(\frac{r - r_p}{r_{\frac{1}{2}} - r_p}\right) \qquad (1)$$

where $\sqrt{\overline{u^2}} / u_o$ = the ratio of the momentum flux velocity at (x,r) to the nozzle discharge velocity

$r_{\frac{1}{2}}$ = the radius at which $\frac{\sqrt{\overline{u^2}}}{\overline{u_o}} = 0.5$

r_p = the radius of the potential cone as determined from the empirical equation $\frac{r_p}{D} = \frac{3.5 - x/D}{7.0}$

Equation 1 is independent of the nozzle discharge velocity and the nozzle diameter.

In the transition region, profiles of the ratio of the momentum flux velocity at any point to that on the jet axis were intermediate between those of the potential cone region and the developed flow region. The profile of this ratio in the developed flow region followed an error type distribution curve shown in Equation 2 in agreement with the findings of Reichardt (5) and of Albertson, et. al. (1):

$$\sqrt{\frac{\overline{u^2}}{\overline{u^2_a}}} = e^{-\ln 2 (r/r_{1/2})^2} \qquad (2)$$

where $\sqrt{\frac{\overline{u^2}}{\overline{u^2_a}}}$ is the ratio of the momentum flux velocity at (x,r) to the momentum flux velocity at (x,0). The momentum flux velocity along the axis of the jet in the developed flow region was inversely proportional to the distance from the nozzle:

$$\frac{\sqrt{\overline{u^2_a}}}{\overline{u_o}} = \frac{1}{2c_1 \, x/D} \qquad (3)$$

in which c_1 is a constant. The nozzle discharge velocity and diameter were found to have only a small effect on c_1. The $r_{1/2}$ distribution was directly proportional to the distance from the nozzle, indicating that in the region of developed flow, the jet spreads linearly.

$$r_{1/2}/D = c_2 \, X/D \sqrt{\ln 4} \qquad (4)$$

where c_2 is constant, and like c_1 is only slightly affected by nozzle discharge velocity and nozzle diameter.

The computation of the momentum flux velocity from the impact tube data depends on the assumptions that the static pressure throughout the jet field is constant and equal to atmospheric pressure, that the flow coefficient of the impact tube varies as the cosine of the angle of attack, and that the flow coefficient is independent of the turbulence characteristics of the flow field. The flow coefficient of the impact tube as a function of velocity was obtained by calibration in a stream of low turbulence level. The angle of attack characteristics of the impact tube were found to deviate considerably from the theoretical cosine function, the flow coefficient being slightly high for angles of attack up to about 40 degrees and becoming negative at angles of attack greater than 60 degrees. The effect of turbulence on the flow coefficient was determined from measurements at several distances behind grids inserted in the throat section of the 0.75 inch diameter nozzle. An appreciable change in the coefficient of the order of 10% was found at a turbulence level of 8%.

In order for the total momentum flux to be conserved, the values of c_1 and c_2 must be equal. Since these differed by as much as 7%, the discrepancy is attributed to the assumptions required for the computation of the momentum flux velocities from the impact tube data.

The introduction of grids into the nozzle throat section had no appreciable effect on the distribution of momentum flux velocity in the jet. The turbulence level of the stream issuing from the nozzle was varied from 0.3 to 8 percent, the turbulence scale being of the order of 0.15 mm. as computed from Dryden's data (4).

Values of the mean velocity $\overline{u}$ at $x/D = 20$ were computed from the momentum flux velocities using the turbulence data reported by Corrsin (3). The entrainment ratio for the jet was then calculated from the mean velocity distribution at $x/D = 20$. The errors introduced in the calculation of the entrainment ratio by assuming that the impact tube measures the mean velocity directly were found to be about 7.5%.

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VITA

The author was born in Columbus, Ohio, on September 30, 1926. He attended public schools in Providence, Rhode Island, Oak Park, Illinois, Champaign, Illinois, and Milwaukee, Wisconsin, graduating from Whitefish Bay High School in 1942. He then attended Louisiana State University, receiving the degree of Bachelor of Science in Chemical Engineering in 1945. While at Louisiana State University in 1945-46 he held the Gaylord Container Corporation fellowship. In the fall of 1946 he entered the Graduate College of the University of Illinois and received the degree of Master of Science in Chemical Engineering in 1948. He held a Research Assistantship in the Engineering Experiment Station under a contract with the Office of Naval Research, N6-ori-71, Task Order XI, from 1946 to 1950. The author is a member of ΑΧΣ, ΤΒΠ, ΟΔΚ, ΦΚΦ, ΦΛΥ and ΣΞ. He has participated in the publication of an article entitled "Air Turbulence and Transfer Processes — Flow Normal to Cylinders" [Comings, E. W., Clapp, J. T., and Taylor, J. F., *Ind. Eng. Chem.*, 40, 1076 (1948)].